Elucidating dingo's ecological roles: contributions from the Pelorus Island feral goat biocontrol project

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ABSTRACT

Understanding the ecological roles of apex predators remains an important field of study. The influence of apex predators on ecosystems can be either profound or negligible in different situations, and uncertainty still exists about the ecological roles of most top-predators, including Australian dingoes. This uncertainly is maintained by a dearth of experimental evidence investigating their roles. Such evidence is indispensable if dingo management is to be evidence-based. In this report, we discuss a recent experiment where dingoes were released on to an island as vertebrate biocontrol tools intended to eradicate feral goats and restore native vegetation being threatened by the goats. The experiment was successful, and the dingoes reduced the goat population to one or perhaps two male goats within ~2 years. This predator introduction experiment elucidated dingo's effects on small livestock, their per capita predation rates, and their invasiveness or their ability to adapt and change their environment. The experiment confirmed that dingoes have the capacity to decimate populations of small livestock species and trigger a trophic cascade by reducing herbivory on vegetation. We encourage further manipulative experiments to explore the ubiquity of these results in different contexts.

Key words: *Canis familiaris* (dingo), invasive species, island conservation, lethal control, total grazing pressure, trophic cascade, wild dog.

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Introduction

Large carnivores are some of the most iconic species on Earth. However, many of them are particularly vulnerable to extinction and a great deal of effort is spent on their conservation and recovery (Hayward and Somers 2009; Ripple *et al*. 2014; Ford *et al*. 2017). Interest in the ecology of large carnivores has increased greatly over the last 25 years subsequent to the much-discussed outcomes of grey wolf (*Canis lupus*) reintroduction to Yellowstone National Park in North America, where wolves have contributed to reduced ungulate densities and its cascading effects on flora and fauna (MacNulty *et al*. 2016). These important, structuring and regulatory roles played by large carnivores are speculated to occur for several charismatic species, although primarily for dingoes (*Canis familiaris*; Glen and Dickman 2005) and grey wolves (Ripple and Beschta 2012). But while the theory is well-developed, for almost all large carnivores there remains an absence of reliable data actually demonstrating their ability to generate trophic cascades (Ripple *et al*. 2014). Ecologists and wildlife managers have therefore called for rigorous, manipulative experiments to demonstrate carnivores' roles and reliably inform carnivore conservation policy (Mech 2012; Hayward *et al*. 2015; Allen *et al*. 2017a).

Dingoes are an ancient and iconic breed of wild-living dog distributed across ~85% of mainland Australia and several offshore islands (Corbett 2001; Johnson 2006). Coarse estimates suggest that there may be over 50,000 adult dingoes on the Australian mainland (Allen *et al*. 2017b). They weigh 15.7 kg on average and are Australia's largest mammalian carnivore (Allen and Leung 2014). Dingoes arrived in Australia about five thousand years ago but are considered a native species in legislation (Fleming *et al*. 2001). Dingoes can have significant negative effects on livestock (e.g. Allen and West 2013; Fleming *et al*. 2014; Allen and West 2015) and some threatened species

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(Coutts-Smith *et al.* 2007; Allen and Fleming 2012) and are therefore subject to coordinated lethal control in many places (Anon 2014). These negative effects are contested by others who assert that dingo's effects on livestock are not substantial (e.g. Forsyth *et al.* 2014; Wallach *et al.* 2017) or that dingo's have net positive effects on some threatened species in some contents (e.g. Letnic *et al.* 2012; Hunter *et al.* 2018). Until recently, however, previous efforts to understand the ecological roles of dingoes have yielded only a collection of snap-shot correlative studies claiming dingoes perform functional roles akin to those of wolves (Allen *et al.* 2013b; Morgan *et al.* 2017). The wide variety of systemic methodological shortcomings typical of this literature means that most of the available information on this subject is unreliable and insufficient for informing dingo conservation or control policy (e.g. Woodman 2011; Allen *et al.* 2013b; Fleming *et al.* 2014; Hayward and Marlow 2014; Allen *et al.* 2017a).

Manipulative experiments that either remove or introduce dingoes "are the only means" for robustly elucidating causal relationships between dingoes and other species and answering fundamental questions about dingo's ecological roles (Glen *et al.* 2007, pg. 496). Such manipulative experiments yield the most conclusive data on dingo function and are indispensable if managers seek to make evidenced-based decisions; anything less merely contributes to hypothesis development (Caughley and Sinclair 1994; Hone 2007). Several dingo population manipulation experiments from across the country have now been completed, yielding consistent results demonstrating that contemporary lethal dingo control practices do not cause trophic cascades primarily because any reductions in dingo densities (e.g. Allen *et al.* 2013a; Allen *et al.* 2014a) and/or changes to their functional behaviour (e.g. Allen *et al.* 2014b; Allen and Leung 2014) are only temporary (see also Eldridge *et al.* 2002; Kennedy *et al.* 2012; Eldridge *et al.* 2016). Trophic cascades are not triggered by temporary reductions in dingo densities or temporary changes to dingo function. But because dingoes quickly recolonised areas where they were experimentally reduced and were therefore not enduringly 'removed' or 'added' in these *in situ* experiments (i.e. immigration and emigration were possible over extended timeframes in the open systems studied), there is presently not a single published report that can experimentally or demonstrably answer the questions '*what happens when dingoes are completely and permanently removed from an ecosystem?*' or '*what happens when dingoes are added to an ecosystem where they have never occurred before?*' (Johnson *et al.* 2014; Hayward *et al.* 2015).

Answering these questions are important for elucidating dingoes ecological roles and evaluating the likely ecological outcomes of dingo removal or addition to various ecosystems, which have both been proposed as management approaches to correct other ecological concerns (Newsome *et al.* 2015; Clark *et al.* 2018). But answering these questions in a scientifically robust way is only possible (1) where dingoes are introduced to ecosystems that have never had dingoes or (2) where dingoes are actually reduced to levels low-enough for long-enough to potentially generate faunal and floral responses. Dingo populations are very resilient to repeated lethal control and achieving substantial dingo population reductions at the large spatial and temporal scales needed is difficult to achieve in open systems on the Australian mainland (Fleming *et al.* 2014). Dingo introduction or reintroduction is also either moot for the 85% of the continent where dingoes already exist or vehemently opposed in the remaining 15% of Australia where extant commercial sheep (*Ovis aries*), goat (*Capra hircus*) and kangaroo (Macropod spp.) enterprises rely on the absence of dingoes (Allen *et al.* 2017b). Introducing or encouraging dingoes under any circumstances should also be approached cautiously given dingo's known and suspected contributions to the historical and contemporary extinctions of several native species and their predicted adverse effects on many others (Johnson 2006; Allen and Fleming 2012).

In our ongoing efforts to acquire more robust data on dingo's ecological roles and inform dingo management and conservation policy, offshore islands offer an excellent opportunity to conduct rigorous, dingo introduction experiments under carefully controlled conditions where their ecological roles can be reliably measured (Terborgh and Estes 2010). Here, we discuss a recent dingo introduction experiment on Pelorus Island in north Queensland to illustrate the value these types of experiments have on elucidating dingo's ecological roles. We do not present all the data or results from this experiment, but rather aim to briefly describe the experiment and discuss how some of the results contribute valuable information on dingo's ability to generate trophic cascades. We further highlight how well-designed manipulative experiments can yield data that inform contested issues that extend beyond the immediate goals of the experiment.

The Pelorus Island feral goat biocontrol project

Pelorus Island (-18.550, 146.496) is a small (4 km^2), volcanic island in the Great Barrier Reef about 10 km off the coast of north-eastern Australia, and was home to ~300 feral goats which were threatening the island's endangered, native flora (Australian Government 2016). While the vegetation canopy is largely intact on much of the island, the understory had been removed in many areas, and exposed bare ground and rock was particularly apparent on several east-facing slopes where severe overgrazing and erosion were occurring (Fig. 1). Previous goat control efforts included aerial shooting and ground shooting, which had occurred for many years but were ultimately considered ineffective by managers due to the ruggedness of the terrain and closed forest canopy. Mustering, trapping, and Judas goat approaches were also explored but considered unlikely to ever be successful

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Fig. 1 – (A) Feral goats grazing on the north-east slope of Pelorus Island, 6 July 2016, showing an absence of palatable vegetation and widespread exposure of bare ground and rock; (B) the first black-and-tan dingo released on to Pelorus Island, 1 July 2016; (C) a small mammal trap on the overgrazed north-east slope of Pelorus Island, 10 December 2015; (D) feral goats grazing on the north-east slope of Fantome Island, 12 November 2015, showing an absence of palatable vegetation and widespread exposure of bare ground and rock. Photo credits: Benjamin Allen.

for the same reasons. Though traditional goat control approaches were considered inadequate, state biosecurity legislation (*Biosecurity Act 2014*) still obligated the local government to remove goats from the island somehow.

A novel and collaborative project involving state government, local government, and university began being seriously discussed in 2013. This collaboration eventually led to the release of two dingoes on to Pelorus Island as vertebrate biocontrol tools intended to eradicate the feral goats and restore native vegetation by alleviating herbivory from goats. The released dingoes were captured from a single site on the adjacent mainland where dingoes were regularly subjected to lethal poisoning and trapping programs to protect cattle. The dingoes were released on to Pelorus Island in July 2016 (Fig. 1). Goats were monitored on the island before, during and after dingo release by an array of camera traps, supplemented by aerial, ground and boat surveys. Small mammal trapping and vegetation monitoring also occurred before, during and after dingo release (Fig. 1). Fauna and flora monitoring efforts concentrated on the overgrazed north-eastern slopes of the islands where vegetation responses were expected to be more easily measured.

Dingoes have never existed on Pelorus Island. Given dingo's home range size in nearby habitats (e.g. McNeill *et al.* 2016; Morrant *et al.* 2017), the island was deemed too small to maintain a self-sustaining population of dingoes following the removal of goats, which was partly the reason why only two males were released. A large, nearby island in the same archipelago (Great Palm Island) has a permanent human population and a relatively large population of free-roaming dogs which frequently accompany humans on boat transport between islands, so the two male dingoes were also desexed to eliminate the possibility of unintentional breeding between the released dingoes and any transported dogs. To minimise the risk of unintentionally introducing any mainland parasites or pathogens to the island that were not already present there, the two dingoes were also treated for parasites and vaccinated prior to release. A similar dingo-goat

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biocontrol experiment was conducted on Townshend Island (70 km^2) in the 1990s, where 16 mostly unrelated, mixed-sex and mixed-age dingoes were introduced and eradicated ~3,000 goats within three years (Allen *et al.* 1996; Allen *et al.* 1998; Allen *et al.* 2012). Given this result, the two dingoes we released were expected to remove the goats from Pelorus Island within ~2 years. Circumstantial evidence from the Townshend Island experiment suggested that allowing dingoes to remain on the island after the removal of goats could contribute to negative effects on some shorebird species, although below-average rainfall during this period is also likely to have influenced the observed effects on shorebirds in that study (L. Allen, unpublished data). Ground surveys and a 'Protected Matters search' conducted during project planning revealed no threatened terrestrial mammal, bird or reptile species likely to be impacted by dingoes (Australian Government 2016). But to facilitate dingo location and euthanasia by firearm should non-target impacts arise and be deemed too great, the two dingoes released on Pelorus Island were fitted with GPS tracking collars expected to last for about two years. In the event that the dingoes could not be euthanized by firearm, a small, delayed-release toxic implant was also inserted under the skin between the shoulder blades of each dingo to ensure that any predation impacts on native fauna did not continue any longer than was necessary to remove the goats. The implants were expected to euthanize the dingoes after approximately two years.

The ultimate purpose of the Pelorus Island goat biocontrol project was about complying with legislative obligations to remove the goats and conserve an endangered ecosystem and its constituent species. Hence, each of the aforementioned operational measures were intended to allow the dingoes sufficient time to remove the goats while mitigating potential environmental risks and complying with legislation governing the way goats and dingoes could be managed. To enhance the scientific value of this goat biocontrol operation, all fauna and flora monitoring procedures that occurred on Pelorus Island were simultaneously repeated on a nearby island which also contained a large population of feral goats (Fantome Island; Fig. 1). The (1) addition of an experimental control or nil-treatment island for comparison, (2) standardisation of fauna and flora monitoring procedures across both islands, and (3) simultaneous implementation of monitoring procedures before, during and after the release of dingoes on both islands elevated the inferential value of this project from a simple observation or correlation to a manipulative experiment capable of demonstrating dingo's ability to cause a trophic cascade. Nearby islands also contained goats and could have been used as replicates of both treated and nil-treated islands, but our available resources did not allow us to simultaneously undertake the experiment on additional islands. We discuss some of the learnings from this experiment that inform debates about dingo impacts on livestock, per capita predation rates, and their invasiveness or ecological roles.

Impacts on livestock

Dingoes can have positive, negative or neutral impacts on economic, environmental or social values, and these impacts vary spatially and temporally (Fleming *et al.* 2012a). This is especially true for their impacts on livestock. Dingoes can kill up to 32% of beef cattle calves under certain conditions (Fleming *et al.* 2012b), although impacts of this magnitude occur sporadically (e.g. Allen 2014; Campbell *et al.* 2019; Allen and Hampton In press). Beef cattle producers estimate that dingoes typically kill 1–7% of calves in most years (Hewitt 2009). Sheep, on the other hand, are much more susceptible to dingo attack. Dingoes can decimate sheep flocks (Payne *et al.* 1930; Barnard 1962) and viably grazing sheep is impossible without intensive dingo exclusion and removal (Allen and West 2013, 2015). Though there is relatively little data to demonstrate it, dingoes are expected to have similar devastating effects on mainland goat populations (Pople and Froese 2012; Bell 2015; Forsyth *et al.* 2019). Experimental data on dingo impacts on beef cattle is available (Eldridge *et al.* 2002; Allen 2014; Campbell *et al.* 2019), but such data is largely unavailable for sheep and goats given that dingoes were historically eradicated from sheep and goat grazing regions long before researchers ever considered trying to experimentally quantify dingo impacts on these types of livestock (Allen and West 2015). Sheep and goat producers in the 1800s learned quickly that dingoes had the capacity to prohibit sheep or goat production (Anon 1852; Payne *et al.* 1930; Barnard 1962).

The relative paucity of experimental data on dingo impacts on sheep and goats have led some to disregard these historical experiences and claim that dingoes are not a major threat to small livestock (e.g. Forsyth *et al.* 2014). Investigating the veracity of the dingo threat can be achieved by conducting manipulative experiments where dingoes are introduced to areas containing populations of small livestock, but conducting such experiments in commercial sheep and goat production regions on the mainland is understandably unacceptable to livestock producers given their experiences. The Pelorus Island goat biocontrol project therefore represents an experiment where the impacts of dingoes on small livestock can be quantified without impacting commercial livestock enterprises.

Given that the two dingoes released on to Pelorus Island in July 2016 managed to reduce the goat population of ~300 to just a few male goats by March 2017 in the presence of small mammal prey (see below), it seems clear that dingoes have the capacity to swiftly decimate small livestock populations in some contexts. Information on dingo impacts on goats from the Pelorus Island project supports the notion that dingoes are a serious threat to small livestock. Goats and dingoes just happened to be the species of interest in this island conservation project, which coincidentally helps inform debates about dingo impacts on livestock.

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Per capita predation rates

As Australia's largest terrestrial predator, understanding dingo's ecological roles has a lot to do with understanding their predation ecology. Investigating what dingoes eat (e.g. Corbett 1995; Allen and Leung 2014; Davis *et al.* 2015; Behrendorff *et al.* 2016; Doherty *et al.* 2019) is the most simplistic way to study their potential predation impacts. But given that dingoes are also scavengers (Allen 2010; Meek and Brown 2016; Behrendorff *et al.* 2018), what they eat is not necessarily the same thing as what they kill, which is why diet studies alone have a limited ability to inform dingo impacts on prey populations (Woodman 2011; Allen and Leung 2012). Data on per capita predation rates is ultimately one of the best forms of information for understanding predation impacts. Such information is available for well-studied carnivores, such as wolves (e.g. Gervasi *et al.* 2011; Vucetich *et al.* 2011; Lake *et al.* 2013; Christianson and Creel 2014), but it has never been adequately investigated for dingoes.

Shepherd (1981) counted and necropsied prey carcasses around a water point in the arid Sturt National Park, New South Wales, over a seven-week period and reported that a group of five dingoes killed 83 red kangaroos *Osphranter rufus* during this time. The daily rate of killing was estimated to be about 0.38 kg of prey per kg of predator, and the rate of killing and the selection for juvenile kangaroos suggested that dingoes could have a direct negative effect on kangaroo densities by limiting their rate of increase (Shepherd 1981; see also Choquenot and Forsyth 2013; Allen 2015; Prowse *et al.* 2015). Moseby *et al.* (2012) introduced seven foxes *Vulpes vulpes* and six feral cats *Felis catus* into a 37 km^2 predator-fenced enclosure in arid South Australia inhabited by a male and female dingo. All seven foxes were opportunistically killed by the dingoes within 17 days of introduction, all six cats died within 103 days of introduction, and dingoes were implicated in at least three of these cat deaths. Allen and Leung (2012) assessed patterns in dingo diet from over 4,000 dingo scats collected in arid South Australia, and used these data to infer that some individual dingoes may consume up to 20 dusky hopping-mice *Notomys fuscus* per day to meet their daily energy requirements. These studies provide some indication of per capita predation rates of different prey by dingoes, but each conclude that much more data are needed to reliably quantify dingo predation impacts on prey populations (e.g. Moseby *et al.* 2012; see also Woodman 2011).

The Pelorus Island dingo-goat project represents a predation rate study with a known number of dingoes and a relatively known number of goats in a closed system. Based on aerial survey and shooting operations conducted in the preceding years, there were approximately 300 feral goats on the island when the two dingoes were released in July 2016. Supplementary aerial shooting efforts in August 2016 removed 45 goats, and opportunistic ground shooting efforts in September 2016 and November 2016 removed an additional three and four goats, respectively. Only a small group of approximately seven adult, male goats repeatedly observed on camera could be found on the island by March 2017 (Fig. 2). These same individual

Fig. 2 – Four male goats from the last group of seven goats on Pelorus Island, photographed together on 26 September 2017.

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goats persisted until March 2018 when five were shot from a helicopter near the water line at the base of a steep and inaccessible cliff. Two additional goats were observed at that time but could not be shot. The last goat observed on Pelorus Island was one large male goat seen on the north-east slopes during a ground survey in April 2018. None have been observed since that time on any camera trap, during an aerial survey in mid 2018, during a ground survey in November 2018, or during six boat surveys circumnavigating the entire island searching the coastal cliffs where goats had previously been most visible. Such coarse information might suggest that per capita dingo predation rates could have been as much as roughly one goat every two days per dingo. However, this estimate is unreliable for a variety of reasons, including (1) the starting population may not have been exactly 300 goats, (2) goat births are not accounted for, (3) we have not accounted for goat deaths unrelated to dingoes (e.g. shot goats, natural mortality), and (4) predation rates are unlikely to be static or linear throughout the period. Refining this coarse per capita predation rate estimate requires a more detailed investigation into the timing of individual goat 'disappearance', which is achievable using the camera trap data collected but not presented here. Camera traps were intended to verify goat eradication, but using them had the added benefit of providing more reliable quantification of per capita predation rates to augment the sparse literature addressing this important but understudied aspect of dingo ecology.

Dingo's ecological roles

Researchers were not present in Australia thousands of years ago when dingoes were introduced and began their expansion across the continent. The available archaeological record implicates dingoes as one primary cause of native species loss and extinction at this time, but concomitant climate changes and advances in aboriginal hunting technologies have also been proposed as alternative or additional mechanisms that may have contributed to recorded fauna declines (Johnson 2006). This absence of information means that we do not know and cannot tell with any certainty to what extent dingoes caused these historical declines. Contemporary studies can elucidate dingo's ability to cause contemporary fauna declines (e.g. Allen *et al.* 2018), but here again, concomitant changes in climate, land use, fauna assemblages and other factors can affect interpretations of dingo's ecological roles, especially when studies are poorly designed and cannot account for these factors (Allen *et al.* 2013b; Allen *et al.* 2017a). Island introduction experiments can inform debates about dingo's invasiveness and elucidate just how quickly dingoes can adapt to new ecosystems, identify and exploit novel prey, and cause changes to their environment.

The dingoes released on Pelorus Island were sourced from adjacent mainland populations and were already accustomed to the general climate and vegetation types they encountered on the island. But neither sheep nor goat populations are present in the source area and the two released dingoes were naïve without any prior experience with this type of prey. The goats on Pelorus Island were also naïve given that they had no prior experience with dingo predation or predation more broadly except, perhaps, any predation from white-bellied sea eagles *Haliaeetus leucogaster* or occasional human hunters. The Pelorus Island dingo-goat project therefore represents a study where dingoes encountered novel prey and goats encountered novel predators. Such information is useful to understand dingo's invasiveness or invasion biology more generally, but it also yields insights into the potential impacts of dingoes on the mainland where they are presently reinvading sheep and goat production regions where they have been absent for several decades (Allen and West 2013; Bell 2015).

The two dingoes were released independently a few days apart, but within hours of release both dingoes moved to the area of the island where goat populations were in their highest densities (the eastern slopes). The dingoes found each other and began associating with each other for the first time a few weeks after release. The dingoes used the eastern slopes of the island exclusively for several weeks until goats became more difficult to find and catch, before expanding their occupation of the island and utilising all of it on a regular basis for the reminder of the study (Fig. 3). During repeated visits to the island, goat behavioural responses to human observers changed from casual disregard, to caution and wariness, to instant fear and flee responses. Goat carcasses showing evidence of predation were also observed from the very first ground survey after dingo release (Fig. 4). The batteries on the GPS collars that were monitoring dingo movements were exhausted after ~2 years, before the implants took effect. At the time the two dingoes were last observed on camera, both were in excellent body condition and appeared healthy in all respects, having increased their weight and general body condition from the time they were released. The speed that dingoes learned to identify and kill goats as a prey source and then exploit that prey source is remarkable. Such behaviour was also observed firsthand in the earlier introduction of dingoes to Townshend Island, when naïve dingoes were observed killing naïve goats within hours of release and within minutes of first encountering each other (L. Allen, personal observation, 8 December 1993). In that experiment, dingoes persisted on Townshend Island and dispersed on to nearby Leicester Island (500 m away at the closest point) despite an absence of terrestrial mammals on both islands, and an absence of surface water on Leicester Island. It took several years of intensive and novel control efforts to finally remove dingoes from these islands (Mulville 2003).

Within months of release, the dingo-induced decline of goats also generated vegetation responses on Pelorus Island. Sets of goat exclusion cages had been placed on both islands at the time of dingo release. On Pelorus

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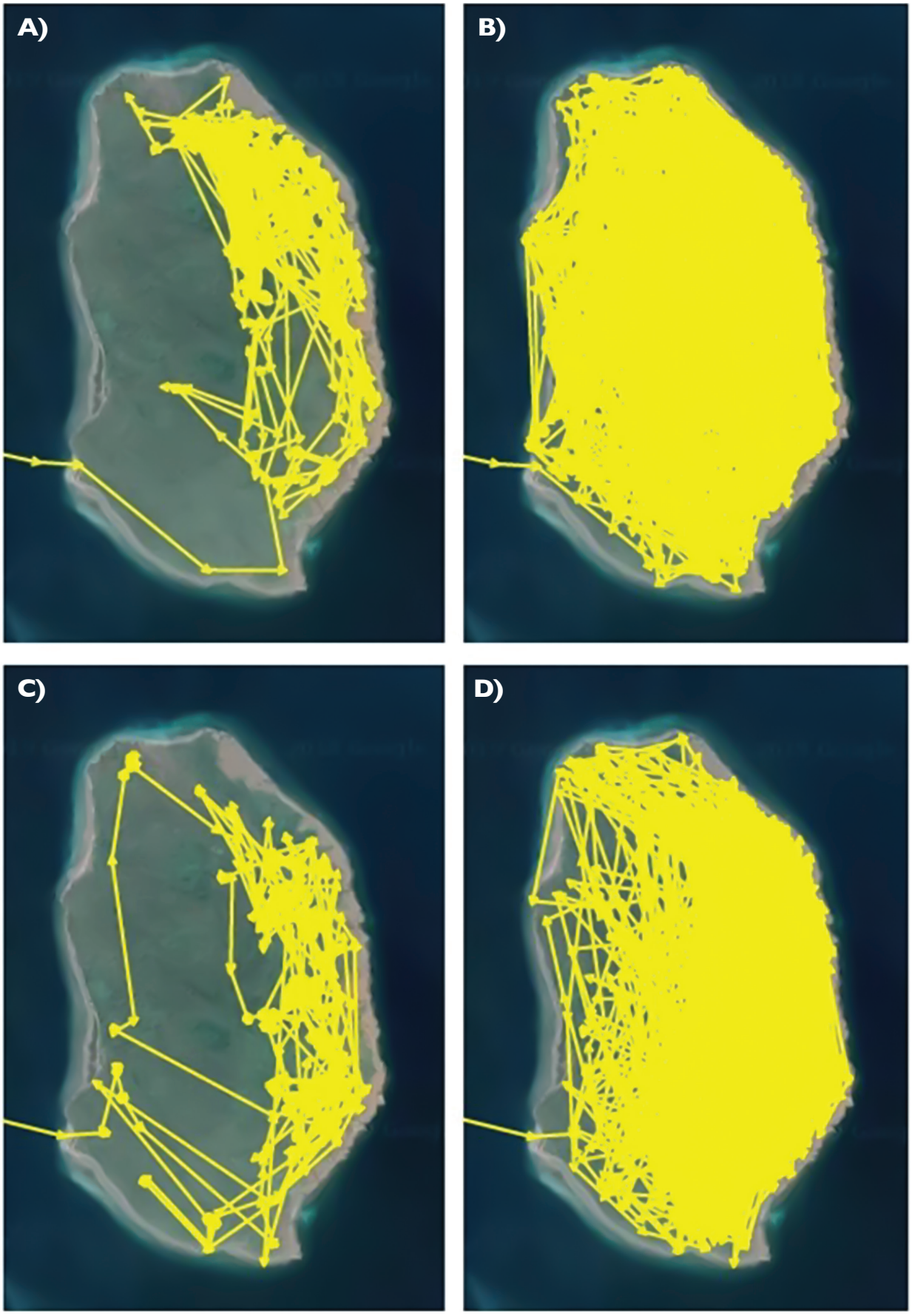

Fig. 3 – Movements of Dingo 1 and Dingo 2 released on to Pelorus Island in July 2016, showing (A) movements of Dingo 1 in the first four weeks after release, (B), all recorded movements of Dingo 1, (C) movements of Dingo 2 in the first few weeks after release, and (D) all recorded movements of Dingo 2.

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Fig. 4 – Remains of a feral goat on the northeast shoreline of Pelorus Island, November 2016, showing signs of predation by dingoes.

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Island, we expected to see vegetation recover just as quickly or nearly as quickly outside the cages (where dingoes were removing goats) as inside the cages (where goats were completely excluded). On Fantome Island, we expected to see vegetation remain suppressed outside the cages (where goats remained uncontrolled) and vegetation recover inside the cages (where goats were completely excluded). We recorded vegetation changes inside and immediately outside each cage twice each year in each wet season and dry season. Observed vegetation responses were exactly as expected (Fig. 5). The results from the Pelorus Island dingo-goat biocontrol project demonstrate that (1) dingoes can quickly identify and exploit novel prey, (2) eradicate or render some prey species functionally extinct, and (3) change vegetation structure remarkably. These experiences support the notion that dingoes indeed exhibit the classical traits of an invasive species and have the ability to cause trophic cascades by reducing herbivory on vegetation. A non-exclusive, alternative view is that dingoes are adept at dealing with a poorly adapted invasive herbivore (Allen and Sparkes 2001).

Conclusions

Manipulative experiments have much greater inferential value than correlations or simple observations (Platt 1964; Hone 2007) and are the only way to demonstrate dingo's ability to cause trophic cascades (Glen *et al.* 2007; Allen *et al.* 2013b). The Pelorus Island dingo-goat project is one of only a few such experiments. Dingoes have been actively introduced (Moseby *et al.* 2012) or passively allowed to naturally recolonise (Allen *et al.* 2013a; Allen *et al.* 2014a) in other experimental studies, but none of these have demonstrated or claimed to have demonstrated a trophic cascade in response to dingo increases or decreases. The Pelorus Island dingo-goat project, along with the earlier Townshend Island dingo-goat project, represent the only two introduction studies we are aware of that have the capacity to experimentally demonstrate dingo's ability to generate a trophic cascade. In these studies, introduced dingoes directly caused the decline of feral goats which, in turn, resulted in a marked increase in vegetation (Allen *et al.* 1996; Allen *et al.* 1998; Allen *et al.* 2012; Fig. 6). Though these island introduction experiments confirm that dingoes can trigger trophic cascades through

Fig. 5 – Vegetation inside and outside goat exclusion cages on Pelorus Island (left) and Fantome Island (right) in July 2016 when dingoes were released (top) and in August 2018 two years after dingo introduction (bottom) to Pelorus Island.

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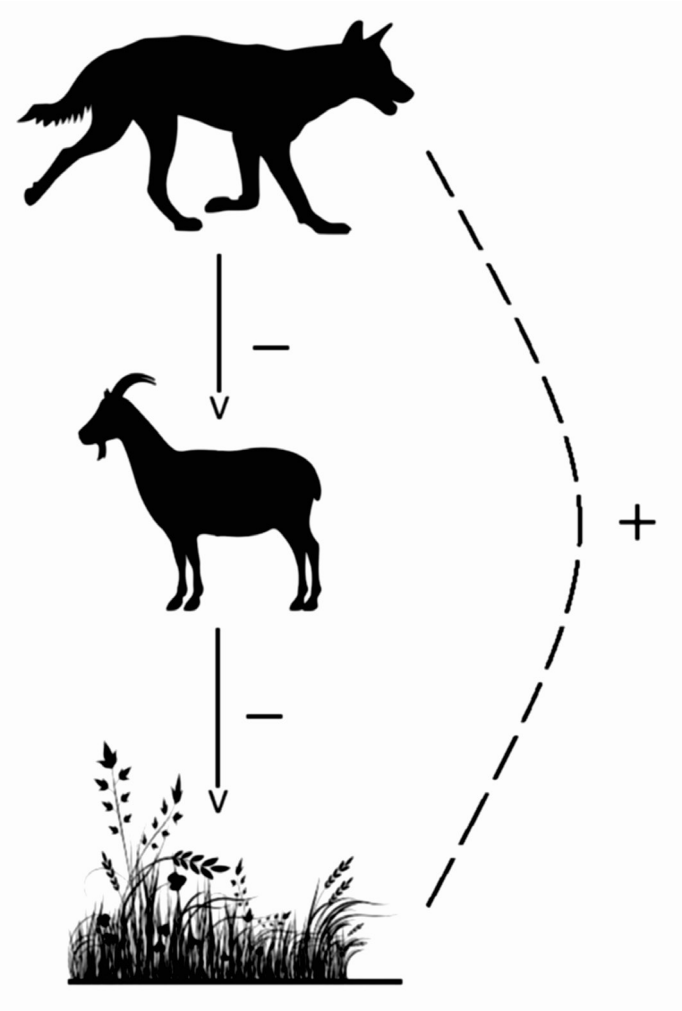

Fig. 6 – Diagrammatic representation of the tri-trophic cascade demonstrated in the Pelorus Island dingo-goat project. Solid lines = direct negative (–) effects. Dashed line = indirect positive (+) effects.

a dingo > herbivore > vegetation mechanism, these experiments offer no information on the hypothesised dingo > mesopredator > small mammal mechanism, which remains unconfirmed (Allen *et al.* 2013b; Allen *et al.* 2015). Experimental data from the Pelorus Island goat biocontrol project also yielded information useful for understanding dingo's invasion biology and impacts on small livestock, including per capita predation rates on goats (see above).

Information from the Pelorus Island goat biocontrol experiment has important implications for those involved in protecting livestock from dingoes and those involved in goat eradication programs on offshore islands. That dingoes can swiftly depopulate areas of goats should be of concern to communities in southern Australia that are reliant on goat grazing and harvesting as a primary source of income (Bell 2015). Left unchecked, dingoes have the capacity to effectively eradicate goats within a few years. Recent experience in southern Queensland further indicates that this will inevitably occur even with intensive and coordinated broad-scale poison baiting that supresses dingoes – complete eradication and exclusion of dingoes is required to maintain viable sheep and goat populations (Queensland Government 2015; Clark *et al.* 2018). In contrast to commercial sheep and goat grazing operations, however, dingo's ability to swiftly eradicate goats should be of great interest to conservationists struggling to manage the impacts of feral goats on offshore islands around the world. Feral goats have devastating impacts on offshore islands (Lee and Stasack 1993; Márquez *et al.* 2013; Pafilis *et al.* 2013; Schweizer *et al.* 2016) and goat eradication exercises can be extremely difficult and very costly (e.g. Masters *et al.* 2018). The experiments conducted on Townshend and Pelorus Islands demonstrate that dingoes can act as effective vertebrate biocontrol agents capable of swiftly removing goats with minimal or negligible non-target impacts under certain conditions. Such conditions are unlikely to be present in all cases and dingoes themselves could pose a serious and legitimate risk to some fauna. But these risks may be manageable with careful implementation of new technologies and several operational strategies that eliminate or substantially reduce these risks.

The Pelorus Island dingo-goat project demonstrates that dingoes can cause trophic cascades by removing herbivores from an ecosystem. The project also demonstrates that dingoes can be a powerful vertebrate biocontrol tool against feral goats. We support the use of manipulative experiments as the only means for confirming dingo's functional roles and encourage greater adoption of this approach to advance our ability to understand and appropriately manage this iconic and important animal into the future.

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